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14. ABSTRACT
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Air Force Data Assimilative Photospheric Flux Transport (ADAPT) Model

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Abstract. As the primary input to coronal and solar wind models, global estimates of the solar photospheric magnetic field distribution are critical to space weather forecasting. These global magnetic maps are essential for accurate modeling of the corona and solar wind, which is vital for gaining the basic understanding necessary to improve forecasting models needed for Air Force operations. In this paper, we describe our efforts and progress toward developing the Air Force Data Assimilative Photospheric flux Transport (ADAPT) model. ADAPT incorporates the ensemble Kalman filter data assimilation technique with a photospheric magnetic flux transport model. The flux transport model evolves the magnetic flux on the Sun using relatively well understood transport processes when observations are not available and then updates the modeled flux with new observations using the ensemble Kalman filter. The data assimilation with the ensemble Kalman filter rigorously takes into account model and observational uncertainties, as well as accounting for regional correlations. Anticipated outcomes of the ADAPT model include improvement in: 1) the estimation of solar corona and polar fields, 2) understanding the nature and behavior of solar super granular diffusion and meridional flows over the solar cycle, and 3) modeling and forecasting the solar wind near Earth.

Keywords: solar photosphere, solar magnetic fields, solar flux transport data assimilation, ensemble Kalman filter
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INTRODUCTION

Open solar magnetic fields associated with coronal holes that extend into interplanetary space, along with strong photospheric magnetic fields from active regions, play a key role in the dynamics of the heliosphere. Active region and coronal hole magnetic fields significantly influence the structure of the solar corona and solar wind dynamics. Though the coronal magnetic field is not readily observable, the large-scale magnetic state of the solar photosphere is regularly recorded from ground-based and spacecraft instruments. The photospheric magnetic field therefore plays a central role in virtually all coronal and solar wind models and thus accurate knowledge of its flux distribution is required to obtain a reliable model of the state of the corona, heliosphere and by extension, the solar wind-magnetosphere interaction.

Currently, the solar magnetic field can only be recorded for approximately half of the solar surface at any given time. Since the rotation period of the Sun as observed from Earth is approximately 27 days, any global map (commonly referred to as a synoptic map) of the solar magnetic field includes data more than 13 days old. The global maps are typically constructed by remapping full-disk magnetograms into heliographic coordinates defined by a fixed rotation rate. The standard fixed synodic solar rotational period used for synoptic maps is 27.2753 days (commonly referred to as Carrington synoptic maps). One of the key drawbacks of Carrington synoptic maps is that they blend space and time since any element of longitude represents the averaging of many magnetograms, for periods up to 10 days, with no correction of, for example, differential rotation.

Flux transport models (e.g., [1] & [2]) attempt to partially compensate for this problem by evolving the

magnetic flux on the Sun using relatively well understood transport processes when observations are not available. The magnetic flux transport model used with ADAPT is a modified version of the Worden and Harvey (WH) model [1]. The WH model includes differential rotation, meridional circulation, super granular diffusion, random flux eruptions, and data merging. The magnetic flux transport as a result of super granulation is simulated using random attractors (see [1] for more details). In addition, the WH model incorporates new data as it becomes available and thus provides a best estimate of the flux distribution on the Sun at any given moment in time.

The WH model, along with most traditional flux transport and synoptic map creation methods, assimilates data simply by inserting or averaging the data directly with the evolving model. These methods make simplifying assumptions about the accuracy of the data and model. In addition, these models do not attach rigorous uncertainties to the forecasts and cannot account for regional correlations in the photosphere.

The advantage of data assimilation is the incorporation of both data and model uncertainties. The ADAPT data assimilation method used with the WH model is the Los Alamos National Laboratory (LANL) data assimilation framework which is an efficient and flexible data assimilation code using an ensemble Kalman filter technique [3]. This framework has already been applied to radiation belt models within the Los Alamos Dynamic Radiation Environment Assimilation Model (DREAM) project [4].

SOLAR FLUX TRANSPORT MODEL

The goal of magnetic flux transport models is to provide the best estimate of the global spatial variation of the solar magnetic field. Including flux transport helps minimize potential monopole moments that periodically occur in Carrington synoptic maps near the solar eastern limb edge of newly merged observed data and during periods when the solar polar regions are not well observed from the Earth.

The modified WH model version now utilizes an ensemble of model realizations using different model parameters constrained by the estimated errors of each parameter. In addition, the modified version allows for the hemispheres to be decoupled with regards to differential rotation and meridional flow. The ensemble of flux transport models estimates the model error required by the Kalman filter. The flux transport parameters of the WH model are expected to vary with the solar activity cycle. For example, the rotation rate of the small-scale background magnetic features varies with the solar cycle [5]. The data assimilated synoptic map ensemble is saved for each time step, with a maximum cadence of 24 hours. For solar cycle parameter analysis, the ensemble will be used to select the best set of model parameters for periods during the past 30 years.

Within the Kalman filter framework, adding data from multiple sources is straightforward. In the near-term, ADAPT will utilize longitudinal magnetogram data from NSO instruments for the years 1977 to present. A critical part of data assimilation is including an accurate measure of the input data uncertainty. The function of the ADAPT Intelligent Front End, shown in Figure 1, is to import, select, and prepare the best available magnetograms for input to the LANL ensemble data assimilator.

LANL DATA ASSIMILATION

Data assimilation is the combination of physical models with observational data to provide a best estimate of the state of a given physical system [6]. The purpose is to find the most likely estimation to the true state (which is unknown) using the information provided by the chosen physical model and the available data considering both of their uncertainties and the limitations of both.

The general principle of the Kalman filter is illustrated in Figure 2. The Kalman filter is a recursive algorithm that automatically takes into account past correlations between different regions of the photosphere until all data is assimilated. The ensemble Kalman filter is based on a Monte Carlo method that can simultaneously estimate the state of the photospheric magnetic field and model parameters. It is a powerful technique that can used as a black box in conjunction with a given physical model. This makes the data-model framework modular where the physics model can be easily replaced and more data can be added with negligible changes.

With the ensemble Kalman filter, all uncertainties are carried along such that each estimate or forecast has an associated uncertainty as well [6]. In addition, past regional correlations are automatically accounted for, and data assimilation can be used to compensate for absent physics in the model [7]. Data assimilation has been used for many decades in terrestrial weather prediction [8]. We have developed an efficient and flexible algorithm based on the ensemble Kalman filter technique [3] and applied it to the WH model.

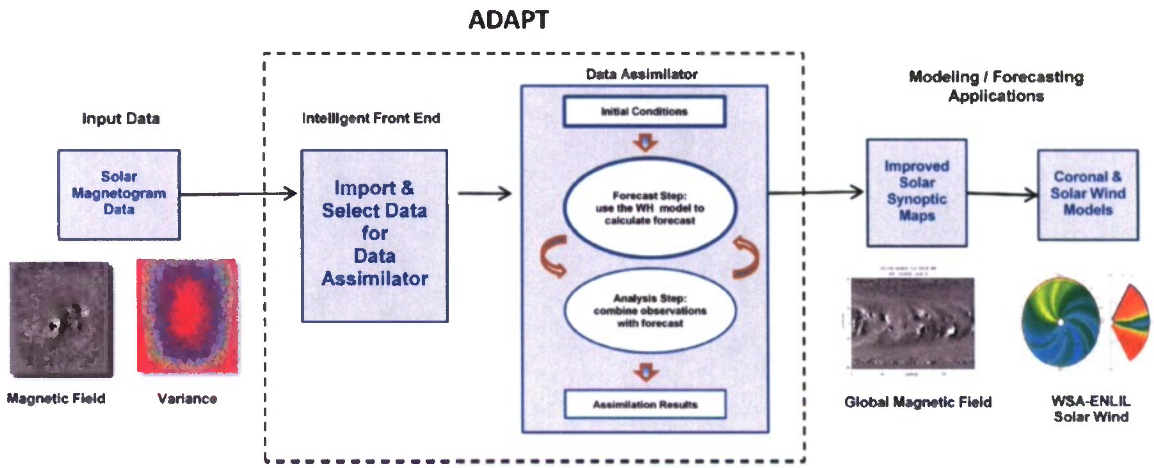

Figure 1. Diagram of the general data flow and processing of ADAPT: the Intelligent Front End imports and selects the best available magnetogram data, along with estimated uncertainties, to be assimilated by the LANL ensemble Kalman filter (see Figure 2) with the latest WH flux transport map of the global solar magnetic field. These maps are then used as input for coronal and solar wind models, e.g., WSA-ENLIL [9].

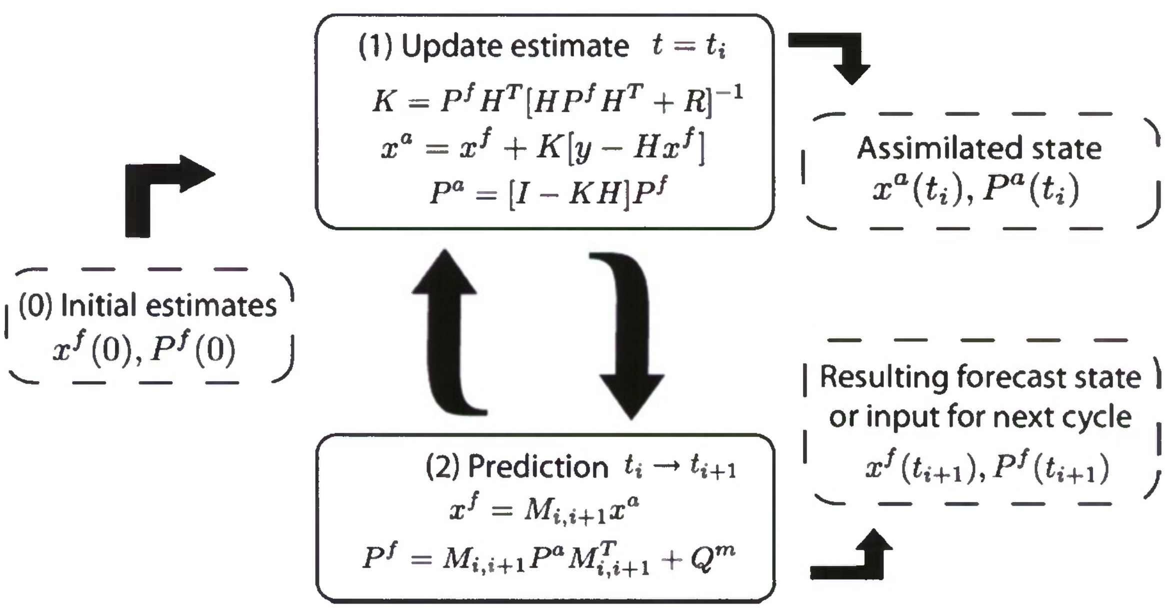

Figure 2. Diagram of the recursive Kalman filter algorithm which combines observations and model forecasts consistently across a global computational domain. The process begins with an initial condition of the magnetic field (step 0), usually a best guess. The Kalman gain is then calculated based on the observations and their uncertainty. The Kalman gain is a weighting factor that will adjust the magnetic field to match the observations (step 1). Next, the coupled model will produce a forecast (step 2) that can then be compared to observations again.

ADAPT MODEL STATUS

A large fraction of the initial development effort has been focused on integrating the LANL ensemble Kalman filter into the WH model. The original WH code was translated from IDL to C. During the translation, the code was modularized and generalized to allow for model ensemble I/O and processing needed with the addition of the Kalman filter. The initial integration of the two codes has recently been completed, and we are now beginning the process of testing and verifying it. The initial baseline tests involve running the coupled code with the LANL ensemble Kalman filter turned on and off so as to insure that the output is consistent with the original WH model results.

During development and initial testing, SOLIS/VSM magnetograms are being used as input data, however, the coupled code is being modified to allow for the incorporation of other data sources, e.g., from NSO/GONG, SOHO/MDI, and HMI/SDO. A preliminary Intelligent Front End (see Figure 1) is under development to select the best magnetograms from multiple instrument sources of the past 3 decades. In addition, GONG has already added variance information as part of their 10 minute magnetogram data product, and we will be testing the model using these new data products soon. With the variance data as part of GONG's magnetograms, we will not have to estimate the data uncertainties in advance, as we have to with the NSO/KPVT data (e.g., by conducting variance studies using past data along with the assumption that the results realistically represent the data for all times), but rather simply ingest these data with their uncertainties already determined. GONG data will serve as an ideal data source for nominal operation of the ADAPT model.

As part of this project, we will be working to quantify the improvement in the predicted solar magnetic field distribution using the ADAPT model over that obtained using more traditional approaches. This is especially true at the poles, which are extremely difficult to measure reliably and to which the coronal and solar wind models are so sensitive. We also plan to better quantify meridional flow and diffusion rates and their variations over the solar cycle. Finally, we will soon use the new data assimilated maps as input to coronal and solar wind models and compare the results obtained (e.g., coronal holes, solar wind) with those obtained using older, more traditional maps and directly with observation.

SUMMARY

We have successfully integrated the LANL ensemble Kalman filter with the Worden and Harvey flux transport model as part of the Air Force Data Assimilative Photospheric flux Transport (ADAPT) model. Improved estimates of the global photospheric magnetic field distribution are important because they serve as primary input to all coronal and solar wind models and thus are essential for gaining the basic understanding necessary to improve forecasting models needed for Air Force operations.

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